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ORIGINAL PAPER

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Gamma radiation calculations and gamma blocker design for the high-energy beam transport region of the European Spallation Source

Karol S. Szymczyk,
Sławomir Wronka

Abstract. The purpose of this paper is to present the Monte-Carlo calculations performed to design a special element called gamma blocker (GB), necessary to stop the gamma radiation in the Accelerator-to-Target (A2T) section of European Spallation Source (ESS) linac. Very high levels of gamma radiation emitted backward from the activated target through the beam pipe could effectively block any human intervention close to the beam transport system. The residual dose rate in the linac tunnel was calculated without and with different GBs as a function of time. The final GB material and dimensions are proposed.

Keywords: ESS • Monte Carlo • Gamma blocker • Gamma radiation

K. S. Szymczyk✉, S. Wronka
National Centre for Nuclear Research
Department of Nuclear Techniques & Equipment
Particle Acceleration Physics & Technology Division
Andrzeja Sołtana 7 Str., 05-400 Otwock, Poland
E-mail: karol.szymczyk@ncbj.gov.pl

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Introduction

The construction of the European Spallation Source (ESS) in Lund, Sweden was begun in the summer of 2014 [1]. ESS source (without neutron instruments) consists of a linear accelerator that delivers a 2 GeV, 5 MW proton beam to a rotating tungsten target. The final high-energy beam transport (HEBT – shown in Fig. 1) region is approx. 50 m long, to allow for possible upgrades, and the proton beam travels through it at the final energy [2]. The region is close to the target, which is activated during the irradiation by a high-energy, high-power beam. Although the losses of the beam in the HEBT region are almost negligible, the intensity of radiation from the activated target is high enough to limit any intervention in the HEBT region during the beam-off time. Such interventions are necessary for repairs, maintenance, or other actions. Therefore, an estimation of residual dose rates is an important task for operational radiation protection, e.g., for the work and dose planning related to interventions in the accelerator facility. The level of residual radiation intensity in the HEBT region depends on the distance from the tungsten target, on the time of irradiation by the proton beam, and on the time elapsed since the last irradiation (the so-called cooling time). Based on Monte-Carlo simulations using the FLUKA package [3], it has been observed that the main problem comes from gamma radiation that can penetrate the HEBT region via the beam pipe. Therefore, a special element to stop the gamma radiation must be designed and installed in the ESS – from here on this element will be called the gamma blocker (GB).

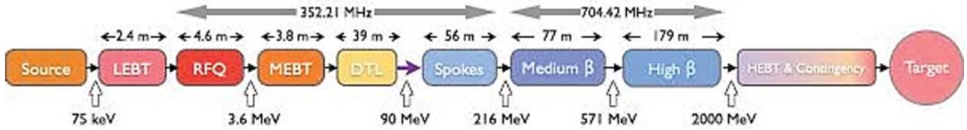

Fig. 1. The ESS linac schema.

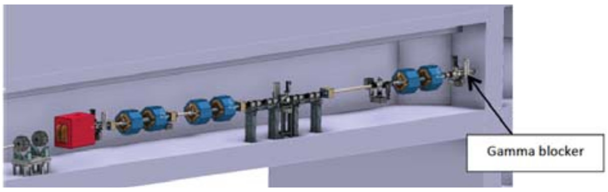

Fig. 2. Schema of the A2T section of the HEBT area.

Gamma blocker location

The GB is foreseen in the accelerator-to-target (A2T) region (see Fig. 2), in the line of sight of a target wheel, upstream of the neutron shield wall (NSW) [1]. Its function is to absorb residual radiation from the activated target during the beam-off mode. During the normal work of the accelerator, GB must not be placed in the beam pipe.

Calculation of residual dose equivalent rates

The FLUKA Monte-Carlo simulation package [3] can provide estimates for residual dose rates for a given irradiation profile and specified cooling time. First calculations were performed to find out the dose equivalent rate (DOSE EQ) inside the A2T tunnel for the following cooling times: 0 (no cooling), 1 hour, 4 hours, 1 month. The source of radiation was located on the surface of the tungsten target. Its spectrum, shown in Fig. 3, was obtained by simulation of 5-year continuous irradiation of the tungsten target by the proton beam with parameters specified in Table 1.

Implementation of the radiation source on the tungsten target surface is shown in Fig. 4. During the simulations, the NSW was nominally 2 m thick, but its final thickness will be determined after detailed neutronic calculations.

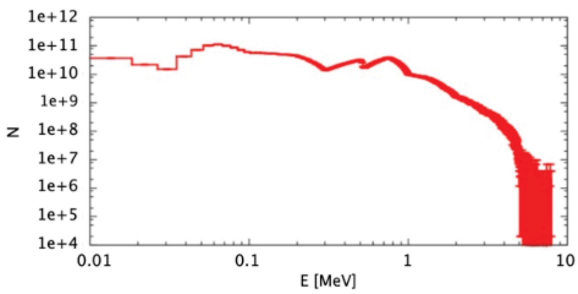

Fig. 3. Implemented gamma radiation spectrum from the external target wheel surface – results of simulations in the FLUKA software.

Table 1. Proton beam parameters used in the simulation

Beam properties	
Energy (GeV)	2.00
Power (MW)	5.00
Pulse current (mA)	62.50
Average current (mA)	2.50

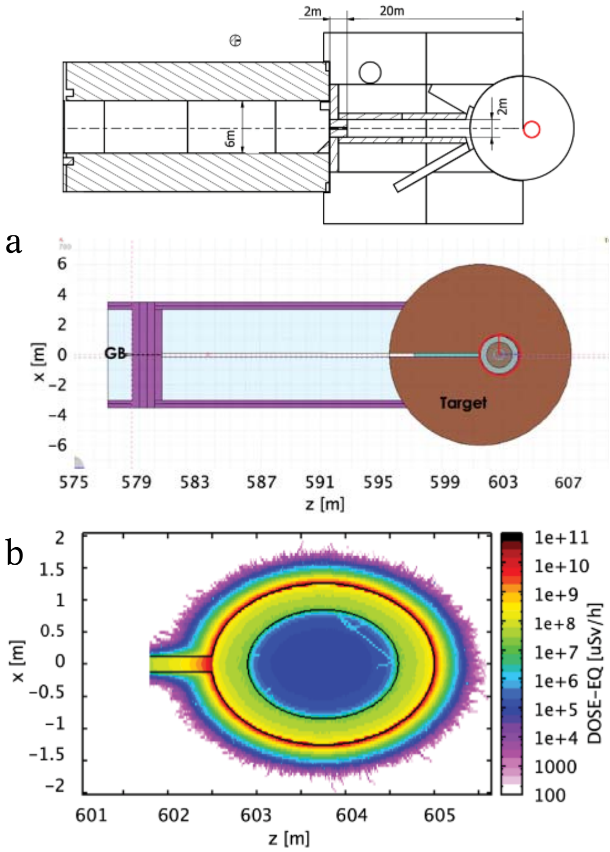

Fig. 4. (a) Schematic view of the target area. Isotropic gamma source was implemented on the external surface of the target wheel (red line). (b) Dose rates obtained after the implementation of the gamma source. The origin of the z-axis starts at the proton source of the linac.

Results

Figure 5 shows the calculated residual dose rates after five years of continuous exposure, inside the accelerator tunnel, in the last part of the A2T section.

Figure 6 shows residual dose rates presented transversally to the accelerator tunnel, at $z = 579.5$ m, for various cooling times [4]. The requirement for GB de-

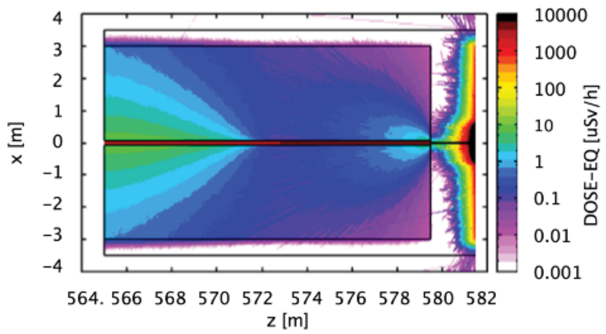

Fig. 5. Residual dose rates after five years of continuous irradiation, and no cooling time. The origin of the z-axis starts at the proton source of the linac.

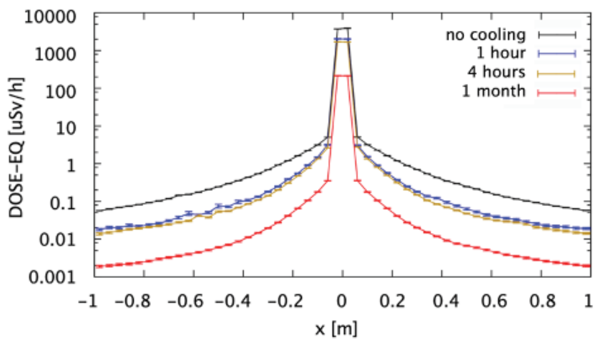

Fig. 6. Gamma radiation dose rate vs. distance from the beam pipe. Projection on X-axis (transverse to the beam axis) at z = 579.5 m, for different cooldown times.

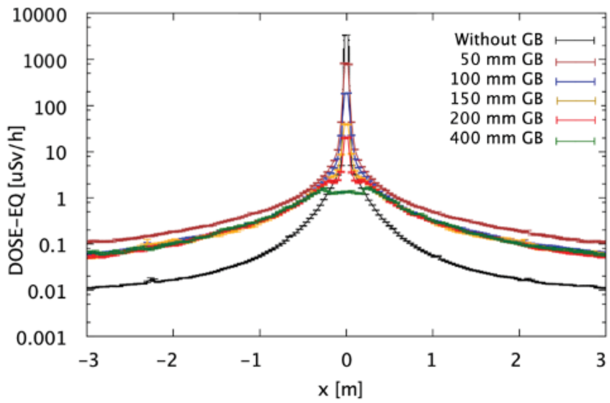

Fig. 8. Residual dose rate vs. distance from the beam pipe. Projection on X-axis at z = 579.5 m after five years of exposure and no cooling time, for different GB thicknesses.

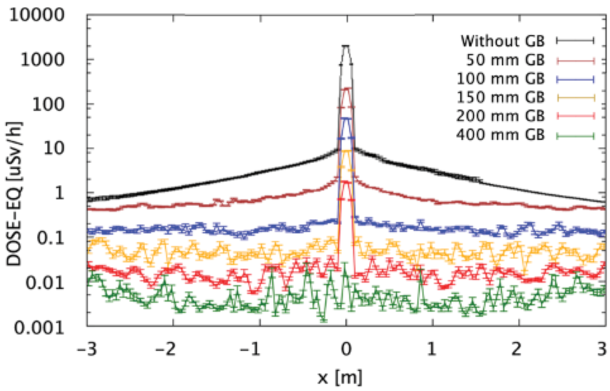

Fig. 9. Residual dose rate vs. distance from the beam pipe. Projection in X-axis at z = 565 m, after five years of exposure and no cooling time for different GB thicknesses.

sign is to limit the dose rate at this position to below 100 μSv/h after five years of continuous irradiation and no cooling time [5]. It can be seen that the radiation dose rate is the sum of two components: (1) central radiation peak related to gammas transmitted through the beam-pipe, directly from the activated target wheel; (2) scattered gamma radiation outside the beam pipe.

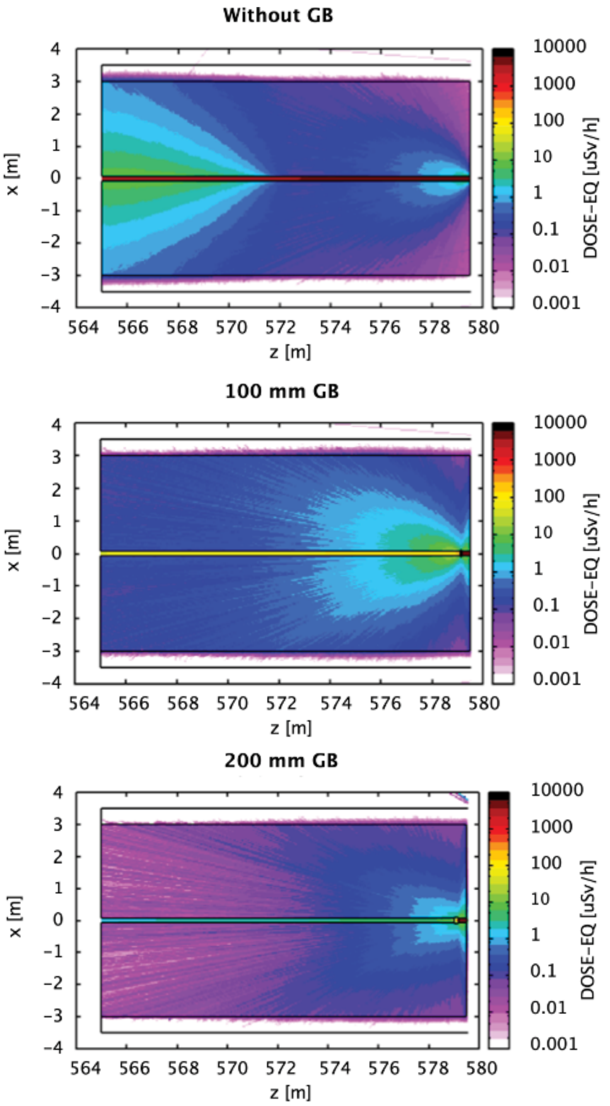

Fig. 7. Dose rate after five years of exposure and no cooling time, for different GB thicknesses.

Installation of the GB element inside the beam pipe should remove the very intensive central peak. Therefore, in the next step, the calculations with the installed GB element were performed to select proper GB thickness. Figure 7 presents residual dose rates in the last part of the A2T section, after five years of continuous irradiation and no cooling time, for different GB thicknesses. All simulations were prepared for GBs made of steel due to the ESS material requirements. GB diameter is equal to 200 mm, while the beam pipe radius is equal to 80 mm.

The level of the dose rate was calculated in two localizations of the A2T section, i.e., on the GB contact at z = 579.5 m and at z = 565 m, where sensitive apparatus is installed. Results in a transversal plane are presented in Fig. 8 (for z = 579.5 m) and Fig. 9 (for z = 565 m).

The GB removes the central intense peak inside the beam pipe. However, it also increases the radiation levels at larger transverse distances in the GB neighbourhood due to radiation scattering.

At z = 565 m, the GB reduces the radiation level both inside and outside the beam pipe. To find the optimal thickness of the GB, the dose rate inside the beam pipe behind the GB, i.e., at z = 579.5 m was calculated. Table 2 and Fig. 10 present these results as a function of the GB thickness, for different cooling times. Beam parameters for presented results are taken from Table 1.

Table 2. Dose rates inside the beam pipe, after five years of exposure and various cooling times, for different GB thicknesses

GB thickness (mm)	Dose rate after five years of exposure (µSv/h)			
	No cooling	1 hour cooling	4 hours cooling	1 month cooling
0	3800 ± 152	2060 ± 103	1700 ± 68	230 ± 9.2
50	850 ± 32	460 ± 14.8	370 ± 11	58 ± 2.8
100	180 ± 7.2	92 ± 3.4	72 ± 2.8	9 ± 0.36
150	40 ± 1.6	21 ± 0.84	18 ± 0.72	2.2 ± 0.09
200	14 ± 0.5	6 ± 0.24	5 ± 0.2	0.8 ± 0.03
400	1.150 ± 0.046	0.850 ± 0.034	0.54 ± 0.02	0.200 ± 0.008

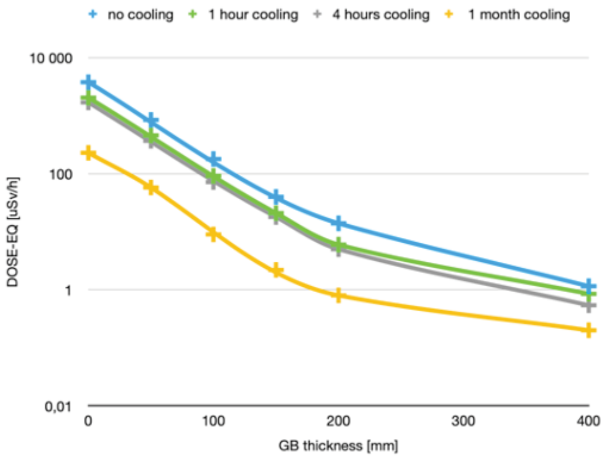

Fig. 10. Residual dose rate inside the beam pipe as a function of GB thickness, after five years of exposure, for various cooling times.

To fulfill the required dose rate limit of 100 µSv/h, a 200 mm thick GB has been proposed for further engineering design, to include the additional safety factor equal 2. Such thickness should allow for access to the zone immediately after switching off the proton beam and moving GB to the "blocking" position.

Conclusion

To allow the intervention in the A2T section of the ESS accelerator, GB is needed to minimize gamma radiation emitted during the beam-off time from the activated tungsten target. This element will be automatically placed inside the beam pipe for the duration of the beam-off time. Before engineering design, Monte-Carlo simulations had to be performed, to select the optimum GB thickness. The residual dose rates in the accelerator tunnel were calculated using the FLUKA package and presented in the article for different GB thicknesses. Taking into account a safety factor equal to 2, a 200 mm thick, 200 mm diameter steel GB was proposed. Such dimensions will limit the dose rate in the accelerator tunnel to a maximum of 100 µSv/h, which is the allowed dose rate limit.

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ORCID

K. Szymczyk http://orcid.org/0000-0001-9159-485X
S. Wronka http://orcid.org/0000-0003-3277-138X

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